

Introduction of *Pinus radiata* for afforestation: a review with reference to Aba, China

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Abstract: *Pinus radiata* D. Don, native to a Californian coastal environment, has been introduced to many parts of the world as an exotic species for afforestation. It is now a major plantation species in the Southern Hemisphere. In 1990, it was introduced to the heavily degraded, dry Min river valley area in Aba prefecture of Sichuan Province, P. R. China. Survival and growth of young trees planted at several sites appear to be reasonable. This review is to serve as an introduction to the large body of literature on *P. radiata* for forest scientists in China. It covers the following aspects: *P. radiata* in its native environment and in ex situ plantations, provenance and genetic variations, environmental limitations and climate niche, diseases and pests, lessons from unsuccessful introductions, and the use of *P. radiata* for ecological restoration. The early growth of *P. radiata* planted in the dry river valley area is briefly described. Potential problems associated with the introduction of *P. radiata* in Aba and future research needs are also identified.

Keywords: *Pinus radiata*; Species introduction; Ecological restoration; Dry river valley.

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Introduction

Pinus radiata D. Don is an evergreen conifer, native to a restricted range along the central coast of California, United States and to Cedros and Guadalupe islands off Baja California in Mexico. Over the last 150 years, it has been introduced to many parts of the world as an exotic species for afforestation. Because of its growth performance, responsiveness to management and cultivation, and the usefulness of its wood for lumber, veneer and pulp, it has become the most widely planted exotic species in the world (Lavery *et al.* 1998), especially in the Southern Hemisphere. In Australia, Chile, New Zealand, Spain and South Africa, it is a mainstay of the forest economy serving domestic markets and generating income from exports (Lewis *et al.* 1993; Lavery *et al.* 1998; Toro *et al.* 1999; Turner *et al.* 1999). *Pinus radiata* has also been planted at a smaller scale or in species introduction experiments in many other countries in both Hemispheres (Lavery *et al.* 1998; Rogers 2002). The worldwide *P. radiata* plantation estate currently exceeds 4 million hectares and is still expanding. These plantations

deflect timber harvest away from native forests, thus contributing to their protection (Sedjo 1999). On eroded lands following deforestation and on degraded marginal agricultural lands, *P. radiata* plantations provide catchment protection, slope stabilisation, flood mitigation and erosion control and generate environmental, ecological and social benefits in addition to timber harvests.

Pinus radiata was introduced to the river valley area in Aba Prefecture of Sichuan Province in China in 1990. This area lies along the upper reaches of the Min River, which flows through a highly mountainous region from the southeast of Qinghai and Tibet plateau down to the Sichuan basin. The prominent geomorphological features of this area are high mountains and deep valleys. The difference in elevation between the river valleys and the mountain peaks ranges from 1500 m to 3400 m. The Min River area was covered in relatively dense alpine and sub-alpine forests about 700 years ago when Marco Polo made his journey to China. However, wars in the distant past and more recent destructive exploitation of the forest resources in the last 50 years have severely degraded a large part of the area. The deforestation, combined with the unique geomorphological characteristics, has changed the local climate and ecological conditions so drastically that the natural forests cannot regenerate and native tree species are difficult to re-establish. As a result, this degraded land has become an arid area covered by little vegetation and referred to by the local people as the dry river valley.

The dry river valley stretches over 150 km through five counties along the Min River, one of the four principal tributaries of the Yangtze River. It covers a total area of more than 150 000 hm². The mean annual rainfall of this area is about

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500 mm, and the mean annual evapotranspiration is greater than 1500 mm. About 80% of the annual rainfall falls during the summer months between May and October. The mean annual temperature ranges from 8.5°C to 13.5°C. The maximum daily temperature is 32°C and the minimum is -14°C. The steep slopes along the valley, usually greater than 20°, are mostly covered by loose and shallow podzolic soils, with sedimentary rocks clearly visible in places. Because it is prone to severe soil erosion and landslides, the dry river valley area is estimated to feed more than 7 million tons of sediment into the Yangtze River each year. To minimise such soil erosion is an essential part of the government forestry and environmental policy (Anonymous 1995).

Pinus radiata was introduced to the dry river valley area as a part of the research work undertaken by Aba Forest Research Institute to search for the most suitable species for reforestation. Among several species of *Pinus*, *Pinus radiata* were considered to be possibly suitable to this area. They include *P. contorta* Douglas ex Loudon, *P. nigra* Arnold subsp. *laricio* (Poiret) Maire, the local native *P. armandii* Franchett and *P. tabuliformis* Carrière. A lot of *P. radiata* seeds for experimentation came from New Zealand Forest Research Institute in the form of a seed exchange. Between 1990 and 2002, experimental plantations with a total area of about 128 hm² were established in three counties of Aba prefecture. Survival and growth of young trees planted at several sites appear to be reasonable and the provincial forestry authority has decided to expand the currently limited plantings of *P. radiata* to cover much of the degraded area. However, to ensure the long-term success of the introduction of *P. radiata*

further research is needed to provide ongoing support to the afforestation program.

There is a vast amount of literature on *P. radiata*. In addition to the large number of journal papers, there are reviews, monographs and books including Scott (1960), Lavery (1986), Lewis and Ferguson (1993), Lavery and Mead (1998) and Rogers (2002). Yet published information available and accessible to researchers in China is scarce. The aim of this paper is not to provide an exhaustive review of, but to serve as an introduction to, the large body of literature on *P. radiata* for forest scientists in China. The review has been written with particular reference to the afforestation and ecological restoration of the dry river valley area. Potential problems associated with the species introduction of *P. radiata* in Aba and research needs are also identified.

***Pinus radiata* in its native environment**

The natural habitat of *P. radiata*, is restricted to three isolated populations on the California coast near Monterey Bay, and the town of Cambria in the USA, and to two small populations on Guadalupe and Cedros Islands of Mexico (Hood et al. 1980; Lavery et al. 1998; Rogers 2002). These disjunct populations lie in a natural range between latitude 28°N and 37°N (Table 1). Three taxonomic varieties have been proposed within the species (Burdon 1992a). The habitats occupied by the five populations differ substantially from one another with respect to soil, elevation, temperature, rainfall, and ecosystem associates (Libby 1997). The topographical range, climate, soils, understorey and growth of naturally occurring *P. radiata* forest types have been described in detail by several authors (Lindsay 1937; Fielding 1961a, b; Forde 1966; Libby et al. 1968; Libby 1997; Lavery et al. 1998; Rogers 2002).

Table 1. Features of the localities in California and Mexico where the three varieties of *Pinus radiata* occur in five natural populations (Modified from Lavery and Mead 1998)

Country	<i>Pinus</i> variety	Preferred population name	Latitude (°)	Altitude /m	Soils	Annual rainfall /mm
U.S.A.(California)	<i>P. radiata</i> var. <i>radiata</i>	Año Nuevo	37	10-330	Fine loams derived from argillites	800
		Monterey	36.5	10-440	Very varied fertility and base status	400
		Cambria	35.5	10-200	Sandy loam with localized poor drainage	500
Mexico (Baja California)	<i>P. radiata</i> var. <i>binata</i>	Guadalupe	29	330-1200	Rocky loam on basalts	150
	<i>P. radiata</i> var. <i>cedrosensis</i>	Cedros	28	290-640	Generally skeletal	150

The climate of the California coast is characterised by low rainfall. Lindsay (1937) compiled extensive meteorological data relating to the areas of *P. radiata* forest on the mainland. Mean monthly temperatures show a relatively even climate with an average difference between the coldest and warmest month of about 6.5 °C in winter and about 17°C in summer. Mean temperatures during the growing season range from 11°C to 16 °C. Mean annual precipitation ranges from about 400 mm to 700

mm, with a minimum annual rainfall of 200 mm and maximum annual rainfall about 1000 mm (Table 2). The climate of Guadalupe and Cedros Islands is Mediterranean-like, with much less precipitation, about 150 mm (Jayawickrama et al. 1993; Lavery et al. 1998) (Table 1), and has greater temperature than that in the mainland areas. Heavy sea fogs are features of the summer climate at all five localities, which provide substantial moisture to trees through crown interception. Beyond the fog-forming zone, summer drought is too

severe to allow *P. radiata* to survive on the Guadalupe and Cedros Islands.

Table 2. Mean minimum and maximum annual rainfall for three locations with natural stands of *P. radiata* (from Lindsay 1937)

Location	Period	Mean annual rainfall /mm	Minimum annual rainfall /mm	Maximum annual rainfall /mm
Monterey	1847 – 1915	424	178	762
Monterey	1948 – 1957	483		
Cambria	1870 – 1922	518	254	1016
Año Nuevo		685		

Apart from the naturally occurring stands, *P. radiata* has also been planted in small clonal plantations, genetic conservation plantings and grown as ornamental trees in many places in California (Lindsay 1937; Libby 1990; Rogers 2002). A representative list of places in California where *P. radiata* has been seen planted as an ornamental, along with notes on growth, the mean maximum temperature of the hottest month and mean annual rainfall can be found in Lindsay (1937). This list is of interest to the introduction of *P. radiata* to the dry river valley area of Aba since it serves as an indicative of the potential growth and survival of *P. radiata* in low rainfall areas. The height of *P. radiata* as ornamental trees with unknown age reached 9–18 m at San Diego where the mean maximum temperature of the hottest months is 23°C and the mean annual rainfall is only 254 mm. At San Bernardino, where the mean annual rainfall is 406 mm and the mean maximum temperature of the hottest months is 23 °C, trees rarely exceeded 10 m in height. At Berkeley, the mean annual rainfall is 660 mm and the mean maximum temperature of the hottest months is 21 °C, and most *P. radiata* trees were 15–21 m high at age of 24 years, with several trees reaching 27–31 m. Following a minimum recorded temperature of -12.7 °C in a two year old clonal plantation at Korbel, in northern California, trees showed symptoms of cold injury, but none was killed (Hood et al. 1980).

***Pinus radiata* in plantations outside USA**

Although its natural range is extremely restricted, *P. radiata* has proved adaptable to many countries in both Hemispheres, with a current plantation estate of just over 4 million hm² throughout the world (Lewis et al. 1993; Lavery et al. 1998; Toro et al. 1999; Rogers 2002). Lewis and Ferguson (1993) provided comprehensive reviews of the distribution, growth habits, stand growth and stand dynamics for *P. radiata* in the Southern Hemisphere. The broad determinants of climatic suitability for successful growth of *P. radiata* have been evaluated for Australia, New Zealand, South Africa and Chile. *Pinus radiata* has been grown over a wide range of latitude, climate and

altitude in these countries (Table 3). In the Northern Hemisphere, plantations of *P. radiata* have been established in the Spanish Basque Region, between latitude 40° and 44°N, with a total area just below 250 000 hm² (Lavery et al. 1998). Other minor growers include Ecuador, Argentina, Colombia, Peru and Italy. In addition to these countries, there have been trials and plantings in many other countries in tropical Africa, tropical South America, Europe, Central Asia, several Mediterranean countries, the west coast of the United States and China (Lavery et al. 1998; Yin et al. 1992; Rogers 2002).

Provenance and genetic variations

Because of the economic importance of *P. radiata* plantations worldwide, there has been widespread interest in its provenance and genetic variations (Burdon 1992b). Even though the total area of the native forests is small, less than 7 000 hm² (Lavery et al. 1998), there is a large amount of genetic variation in *P. radiata* in terms of growth rate, form, disease resistance, drought tolerance and resistance to frost damage (Eldridge 1997b). There also is a high degree of provenance by environment interaction (Ades et al. 1997).

Forde (1964a-d) was the first to report differences in a number of morphological traits between the natural populations of radiata pine in California. Seeds collected by Forde from the mainland populations were subsequently planted in combined provenance-progeny trials in New Zealand (Burdon et al. 1973; Burdon et al. 1977). In Australia, the first provenance trials embracing the three mainland populations of *P. radiata* were planted in the Australian Capital Territory in 1933 (Fielding 1961b). A more comprehensive seed collection was undertaken in 1978 by a combined Australia-New Zealand team in the five natural populations (Eldridge 1978). These 1978 seed collections enabled more systematic assessments of the growth performance of *P. radiata* provenances in different countries including Australia, Chile, New Zealand, South Africa and Turkey (Toplu et al. 1987; Falkenhagen 1991; Jayawickrama et al. 1993; Burdon et al. 1997; Johnson et al. 1997). In Australia and New Zealand alone, a total of 115 provenance trials and genetic conservation plantings of *P. radiata* have been established using seeds collected in the native stands (Eldridge 1997a, b; Burdon et al. 1998). The provenance trials compared mostly growth rates, form, wood properties, and resistance to diseases for commercial plantations. Variation in resistance to pathogens and pests varies within all populations of *P. radiata* and is often highly heritable, offering opportunities to select and breed for resistance (Simpson et al. 1990b; Burdon et al. 1992; Burdon 1992b). Of the provenances tested in New South Wales for resistance to the foliar pathogen *Dothistroma septosporum*, Cambria was the most susceptible (Ades et al. 1991). A putative hybrid *P. radiata* var. *radiata* x *P. radiata* var. *binata* was the most susceptible to pine woolly aphid *Pineus pini* (Simpson et al. 1990a). The 1978 seed collection also enabled detailed examinations of the genetic-architecture of *P. radiata* (Plessas et al. 1986; Moran et al. 1987; Moran et al. 1988).

The published results from provenance trials in several countries and some unreported results were summarized by Eldridge (1997b). Over a range of sites well suited to growing *P. radiata*, Monterey and Año Nuevo are generally the best of the five native populations for growth rate. However, on more difficult and less productive sites, a clear pattern has not emerged. For sites that are almost too cold for radiata pine, the Año Nuevo provenance is clearly the most cold-tolerant (Burdon 1992b). In Ireland and southern England where *P. radiata* is at the limits of its frost tolerance, the Guadalupe population is the healthiest (Lavery et al. 1998). In the Basque country of northern Spain, the Año Nuevo provenance was less affected by the unfavorable climatic conditions in winter,

although Monterey population showed the best overall performance among the three mainland provenances (Espinel et al. 1995; Aragones et al. 1997).

For marginal sites with infertile shallow soils and low rainfall, the Monterey population is sometimes superior in growth to that in Año Nuevo. At an extreme site in the mid-north of South Australia (Wirrabarra, lat. 33°03'S, long. 138°11'E, 200 km north of Adelaide), the growth of the Guadalupe provenance was equal to that of Monterey and Año Nuevo, Cambria was next best and Cedros was inferior (Boardman et al. 1997). In a study over a wide range of sites in New South Wales, Cambria provenance was slightly superior in growth rate to the Año Nuevo and Monterey populations on two of the driest and infertile sites (Johnson et al. 1997).

Table 3. Climatic tolerances of radiata pine in some major production regions (from Lewis and Ferguson 1993)

Region		Mean Annual precipitation/mm	Mean annual temperature /°C	Mean temperature of Coldest month /°C	Mean temperature of hottest month /°C	Absolute minimum temperature /°C
Natural habitats		420-700	13-15	10-11	16-18	-7
Australia	Bathurst	650-950	11-13	0.4-0.6	24-28	-7 to -9
	Tumut	800-1300	11-14	0.5-0.8	25-30	-7 to -10
	Mt Gambier	650-800	13-14	4-6	25-28	-2 to -4
New Zealand	Kaingaroa	1300-1500	10-13	7-9	11-19	-6 to -9
	Nelson (Golden downs)	1300	10.5	4.6	15.7	-9.4
	Canterbury	700-850	11-12	5-6	15-17	-5 to -7
	Southland	960-1000	8-10	3-5	13-15	-9 to -10
South Africa	Cape Province	906-1095	9-12	9-11	10-13	-3
Chile	Coastal cordillera					
	Northern part	450-950	13-15	10-12	16-18	6-8
	Central part	1300	12-13	8-10	16-17	4-6
	Southern part (Valdivia)	2349	11.9	7.7	17.0	4.5
	Central valley					
	Central part	1000-1300	13-14	7-8	20-21	3-5
	Southern part (Temura)	1403	11.9	7.7	17.0	4.1
	Andean foot hills	No records				

Environmental limitations and climatic niche

Booth (1990) used six climatic criteria i.e. mean annual rainfall, rainfall regime, dry season length, mean maximum temperature of hottest month, mean minimum temperature of coldest month and mean annual temperature, to produce a global scale mapping of regions suitable for commercial plantations of *P. radiata* through data interpolation. The map largely covers the climatic tolerances of *P. radiata* in the various major production regions of the world as shown in Table 3. Successful commercial plantation is generally limited to the temperate zone and those subtropical regions where there is limited incidence of damp-heat in summer, or where there is minor incidence of low temperature extremes in winter and untimely frost (Lewis et al. 1993). Extremes of low temperatures, rather than average minima, are major

reason for the species not finding a niche in most Northern Hemisphere countries within the suitable latitudinal range with adequate rainfall. Both the absolute minimum and the timing of the frosts are relevant (Lavery et al. 1998).

Pinus radiata is adaptable to a wide range of soils, from deep sands through to heavier, less well-drained clays or podzols. It prefers deep, well-drained soils with good moisture retention and adequate nutrients (Lavery et al. 1998). Where summer drought or soil moisture deficit is too severe, *P. radiata* will not successfully establish or will be prone to repeated dead topping. A more comprehensive discussion on the environmental limitations and climatic niche of *P. radiata* can be found in Lavery and Mead (1998).

Diseases and pests

In its native environment, *P. radiata* is mainly affected by a number of serious pathogens including one dwarf mistletoe,

two gall rusts and two root diseases (McDonald *et al.* 1990). The dwarf mistletoe (*Arceuthobium occidentale* Engelmann) infects trees of all ages. One species of *Arceuthobium*, *A. pini* Hawksworth and Wiens, occurs on species of *Pinus* in southwestern China. It is not known whether *P. radiata* is susceptible to *A. pini* (Hawksworth *et al.* 1996). Western gall rust (*Peridermium harknessii* J.P. Moore) and coastal gall rust (*Peridermium cerebroides* Meinecke) can cause significant damage to young trees. *Pinus radiata* trees in California are known also to be sometimes infected with species of *Coleosporium* and *Cronartium*. All three of these rust genera occur in Sichuan. The two root disease pathogens are *Heterobasidion annosum* and *Armillaria mellea*. Since the 1980s, pine pitch canker caused by *Fusarium circinatum* has become a serious disease of *P. radiata* in California (Gordon *et al.* 2001). The disease is restricted to the foggy coastal regions in California and is more severe closer to the coast. *F. circinatum* is a pathogen of quarantine concern that could be introduced to China on infected pine seed (Gadgil *et al.* 2003).

Although many insects feed on the needles, twigs, branches and stems of *P. radiata* within its natural range, only few of these cause significant damage. They include four bark beetles (*Ips mexicanus* (Hopkins), *I. plastocephalus* LeConte, *I. confusus* (LeConte), *Dendroctonus valens* LeConte) and a weevil (*Pissodes radiatae* Hopkins); all are cambium feeders (McDonald *et al.* 1990). *D. valens* was detected in pine forests in China in 1999 and has spread to four provinces (Hebei, Henan, Shaanxi and Shanxi) infesting over half a million hectare of forest and killing more than 6 million *P. tabulaeformis* trees (Li *et al.* 2001; Yan *et al.* 2003). The pest is thought to have been introduced to China in unprocessed logs imported from the west coast of the U.S.A. in the 1980's (Yan *et al.* 2003). *D. valens* is a widespread pest of *Pinus* in North America but is generally regarded as a secondary pest (Smith 1971; Britton *et al.* 2002). In China several consecutive years of drought are thought to have favoured the outbreak of *D. valens* (Li *et al.* 2001). In California *P. radiata* is the species most frequently killed by *D. valens* (Smith 1971). Several species of *Ophiostoma* and their anamorphs are vectored by *D. valens* and some of which are pathogenic to pines (Klepzig *et al.* 1991). Should *D. valens* spread to Aba prefecture, its management will be a high priority in the *P. radiata* forests. Other insects causing minor damage in California include aphids, borers, caterpillars, moths and a pine cone beetle, *Conophthorus radiatae* Hopkins (McDonald *et al.* 1990).

Outside its native range, *P. radiata* plantations are affected by mostly fungal infections that cause needle and stem diseases, sapstains and root rots. Lewis and Ferguson (1993) listed the more serious diseases that can significantly reduce growth and cause mortality in stands in the four major *P. radiata* growing countries in the Southern Hemisphere. Eldridge and Simpson (1987)

reviewed control measures for some introduced forest diseases in Australia. The most common disease of *P. radiata* and associated pathogens are given in Table 4. Among them, *Sphaeropsis sapinea* is the most significant disease in *P. radiata* plantations in New South Wales, Australia, causing widespread top death and mortality of drought stressed trees. This pathogen has already been isolated from two trees growing in the courtyard of Aba Forest Research Institute. The relatively low rainfall in Aba is unfavourable to development of epiphytotes of needle cast pathogens such as species of *Mycosphaerella* and their anamorphs, or to members of *Rhytismataceae* including species of *Lophodermium* or *Cyclaneusma* (Ades *et al.* 1991; Choi *et al.* 1991).

Pine wilt nematode, *Bursaphelenchus xylophilus* (Steiner & Buhrer) Nickle was killing large numbers of *Pinus* trees in East Asia (Wingfield 1987) and was first detected in China in 1983 (Yang *et al.* 1989). It is thought this nematode has been introduced from North America perhaps via Japan. *Bursaphelenchus xylophilus* has been recorded killing pine trees in Anhui, Guangdong, Hong Kong, Jiangxi, Shandong provinces in China. The nematode has been isolated from 49 host species in China plus another 21 by host inoculation (Song 2001). The nematode is vectored by species of *Monochamus* (Coleoptera: Cerambycidae) (Linit 1988) and species of this genus are known to occur in Sichuan. *Pinus radiata* is considered as relatively resistance to *B. xylophilus* (Bain *et al.* 1988) but is now known to be susceptible to a Chinese species, *B. hunanensis* Yin, Fang & Tarjan (Yin *et al.* 1988), detected in 2000 in dying *Pinus* trees in Melbourne, Australia.

Table 4. The most common diseases of *P. radiata* and pathogens in ex situ plantations

Disease	Pathogen
Needle blight	<i>Mycosphaerella pini</i> E. Rostrup apud Munk and its anamorph <i>Dothistroma septosporum</i> (Dorog.) Morelet
	<i>M. dearnessii</i> Barr, <i>M. gibsonii</i> Evans
Needle cast	<i>Cyclaneusma minus</i> (Butin) DiCosmo, Peredo & Minter
	<i>Lophodermium</i> spp.
Stem disease (dieback or shoot blight)	<i>Sphaeropsis sapinea</i> (Fr.) Dyko & Sutton.
	<i>Amylostereum areolatum</i>
Sapstains	<i>Ceratocystis</i> spp. and anamorphs. <i>Ophiostoma</i> spp. and anamorphs.
	<i>Armillaria novae-zelandiae</i> (G. Stev.) Herink
	<i>Armillaria limonea</i> Stevenson
Root rots	<i>Junghuhnia vinctus</i> (Berk.) I. Hood & M. Dick
	<i>Phytophthora cinnamomi</i> Rands
	<i>Phytophthora cryptogea</i> Pethybridge and Lafferty

The root pathogen genera, *Armillaria* and *Heterobasidion*, are widely distributed, with species having restricted geographic distributions and host ranges. Two species of *Heterobasidion* are known from China but there is no information on their pathogenicity to *P. radiata* (Dai *et al.* 2002, 2003).

Armillaria mellea occurs in both California and China (Jacobs et al. 1994; Mohammed et al. 1994) but is sensitive to low soil moisture potentials (Whiting et al. 1999) and thus unlikely to be a serious pathogen in pine plantations in the Min River valley. The pathogenicity to *P. radiata* of the numerous other species of *Armillaria* known from China has yet to be determined.

Insects can also cause significant damage to *P. radiata* plantations outside of its native range. In the Southern Hemisphere, a major pest is sirex wood wasp (*Sirex noctilio* F.) which, with its symbiotic fungus *Amylostereum areolatum* (Fr.) Boidin, can cause widespread mortality in stands of any age (Madden 1988). In 1987 alone 1929 hectares of *P. radiata* plantation in South Australia and Western Victoria experienced more than 10% tree mortality with over 1.75 million trees killed (Haugen et al. 1990). Eldridge and Simpson (1987) reviewed control measures for some introduced forest pests in Australia. Twelve species of Siricid wasps, though not *S. noctilio*, occur in China (Xiao et al. 1983), but none is considered to be a pest of national significance. *Sirex rufiabdominis* Xiao & Wu is a significant pest of *P. massoniana* in Zhejiang. *Sirex noctilio* is endemic to regions to the north of China including Siberia and Mongolia (Spradbery et al. 1978), and research using climate matching has predicted it to be able to establish in China (Carnegie, pers. comm.). The recent discovery of California pine aphid, *Essigella californica* Essig in Australia and its apparent rapid dispersal across the country is causing significant concern (Carver et al. 2000). Research is being undertaken to quantify apparent significant losses of productivity associated with this insect in Australia.

In Chile, shoot borers (*Phyaconia buoliana* (Schiff)) are more of a problem (Lewis et al. 1993). Pine woolly aphids (*Pinus pini* L.) can reduce growth rate and cause progressive suppression of infested trees (Simpson et al. 1990a, b). It is not known if *P. radiata* is susceptible to Japanese pine needle scale, *Hemiberlesia pityophila* Takegi or fall budworm, *Hyphantria cunea* (Drury) both of which have established in China and become damaging pests (Britton et al. 2002).

Bark beetles that present a risk to the health of *P. radiata* plantations in Australia, New Zealand and South Africa are *Hylastes ater* (Raykull), *H. angustatus* (Herbst), *Hylurgus ligniperda* (FABR.) and *Ips grandicollis* (Eichhoff) (Lewis et al. 1993; Chapman 1999). Two examples of moth causing damage to plantations are the pine tree emperor moth (*Nudaurelia cytherea* subsp. *cytherea*) in South Africa and the European pine shoot moth (*Phyaconia buoliana*) in Argentina (Lewis et al. 1993; Lavery et al. 1998). In New Zealand, caterpillars feeding on needles can cause defoliation (Chapman 1999), and in Australia significant defoliation has resulted from isolated outbreaks of native looper caterpillars (Lepidoptera: Geometridae).

Lessons from off-site plantings of *P. radiata*

Many other countries in tropical Africa, tropical South America, Europe, Central Asia, China, several Mediterranean countries and the west coast of the United States have or have had a specific interest in *P. radiata* as a potential plantation species (Miller 1974; Lavery et al. 1998; Yin et al. 1992). There are a number of cases where attempts of growing *P. radiata* have failed as a result of what are generally termed off-site syndromes, which can often represent a response to several interacting factors rather than to an individual factor acting in isolation (Lavery et al. 1998).

A particular example of such a failed attempt in China is the introduction of *P. radiata* to Changshun county, Guizhou, a province neighbouring the southeast of Sichuan. The climate there is characterised by damp summer heat. The mean average temperature in the hottest month (July) is 24 °C and the mean maximum temperature is greater than 30 °C. Mean annual precipitation is about 1330 mm but can be greater than 1500 mm in wetter years. During summer relative humidity is well over 80%. *Pinus radiata* seeds from New Zealand were used to establish trial plantings in 1988. Although early growth seemed very promising (Yin et al. 1992), later performance failed largely due to disease and pest attacks associated with damp summer heat.

A number of such cases where off-site plantings of *P. radiata* have experienced major problems or completely failed are listed in Table 5 based on the comprehensive review of Scott (1960), Lavery (1986), Lavery and Mead (1998) and the case reported by Yin and Deng (1992) in China. In addition to the listed cases, experiences from several other southern African countries where *P. radiata* was introduced for afforestation have been generally negative. These unsuccessful introductions highlighted the climatic, environmental and edaphic limitations and forest health risks posed to introducing *P. radiata* for afforestation beyond its ecological niche and its range of biologically safe growth environment.

The use of *P. radiata* for ecological restoration

Pinus radiata has long been used for ecological restoration including catchment protection, slope stabilisation, flood mitigation and erosion control. During 1940-1960, it was planted primarily to control erosion in the coastal range of Chile, where the intense agricultural and cattle-grazing activities developed during the eighteenth and nineteenth centuries on forest land caused severe erosion in an area of over 4 million hm². On these soils, abandoned by agriculture and cattle raising by the mid-nineteenth century, *P. radiata* plantations were established to stop the erosive processes and create the basis for an outstanding forest industry (Toro et al. 1999). Over much of the degraded land in Chile, *P. radiata* has been found to be a species capable of growing in eroded soils where native forest species of economic importance are difficult to establish (Toro et al. 1999), a case similar to the situation in Aba, China. Now plantations of *P. radiata* in Chile help to

help to protect the soils against erosion and to re-establish destroyed ecosystems. In addition, the establishment of *P. radiata* plantations in rural areas has stimulated strong social development and so reduced the

migration of people toward urban zones. The planted forests have provided significant ecological, economic and social values in Chile.

Table 5. Examples of off-site introductions and plantings of *P. radiata*

Country	Region	Period	Scale	Principal limitations
Argentina			Commercial	European pine shoot moth <i>Phyacionia buoliana</i>
Brazil	South-Eastern counties (Cornwall, Devon and Dorset)	1940s	Minor acreage	Unsuitable climate, Dothistroma needle blight and other pests
Britain	Southern England		Trial plantings	Untimely spring and autumn frosts
China	Guizhou Province	1988-2000	Experimental	Damp summer heat and associated disease and pest attacks
Ecuador	Sierra mountains -low latitude and high-altitude sites between 2500 m and 3600 m	1970s	Several thousand hectares	Fungal diseases
France	Southwest coastal districts			Untimely spring and autumn frosts
Kenya		1945-1960s	Approximately 15000 hm ²	Widespread needle cast and die-back caused mainly by Dothistroma septosporum
	East Texas, Southeast USA		Planting ventures	Summer rain, damp heat and associated disease and pest attacks
USA	Oregon		Christmas and ornamental trees	Minimum daily temperature below -18°C for four days in succession killed all young trees and those aged up to 30 years
	West coast, from San Diego to British Columbia		Amenity plantings	Low temperature extremes, frosts, midsummer heat, disease and pest attacks
Zimbabwe	Eastern Highlands	1928-1934	Commercial	Widespread needle cast and die-back caused mainly by Dothistroma septosporum

Much of the hill country of the East Cape region of the North Island of New Zealand is prone to serious erosion (Watson *et al.* 1999). The transformation of native forests to grassland for grazing on the hill country with steep slopes and erodible soils that are subject to high intensity rainfalls resulted in increased runoff, serious flooding and accelerated erosion. In 1988, a large cyclonic storm in the East Coast region of North Island initiated widespread and severe land sliding (Marden *et al.* 1993; Ekanayake *et al.* 1997). On this steep unstable hill country tree planting plays an important role and the main species for reafforestation of the worst-eroded areas is *P. radiata* (Wilkinson 1999). Afforestation of grasslands with *P. radiata* may reduce water yield and associated stream responses and flood peaks by 25%-50% five to ten years after planting (Fahey 1994).

Pinus radiata roots are considered to be a major contributor to soil strength and slope stability through mechanical reinforcement given by the root system to the erosion prone hill soils (Ekanayake *et al.* 1997). Watson and O'Loughlin (1990) hydraulically excavated 13 *P. radiata* trees from three stands on sites with slope ranging from 15° to 26° at Raukumara Range on the North Island. Mean stump diameter was 21, 37, and 60 cm, stand biomass of roots was 9, 67 and 151 tonnes/hm² at a stocking of 253 stems/hm² for the three age classes respectively. Lateral roots had a maximum length of 4.7, 6.4 and 10.4 m at ages of 8, 16 and 25 years. Vertical roots

grew to depths of 2.1, 2.6 and 3.1 m for the three age classes. The lateral roots of *P. radiata* growing on steep sites often grew predominantly across slope and down slope and distributed in the upper 1 m of the soil profile. Planted *P. radiata* forests can establish root system with sufficient strength by year 8 to contribute significantly to soil stability, and by year 30 *P. radiata* has probably attained its maximum root spread and soil reinforcement capacity (O'Loughlin 1985). Allometric relationships between total root weight (*W*) and tree diameter at breast height (*D*) for *P. radiata* can be found in Heth and Donald (1978) and Watson and O'Loughlin (1990).

The root system reinforces soil and stabilises slope through three general mechanisms as suggested by O'Loughlin and Zhang (1986). Firstly, vertical roots that extend across potential failure planes and into stable subsoils can provide a stabilising effect on an unstable upper soil mantle. Secondly, tree root systems provide lateral strengthening of the soil mantle, usually not more than 1 m deep, that contributes to the stability of the underlying substrates. Thirdly, the structural roots and central root bole provide localised centres of increased reinforcement that tends to act as supporting buttresses. In addition, the litter layer acts to slow and hold falling rain. As the litter layer becomes thicker, more falling rain will be able to infiltrate into the soil and so reduce run-off and soil erosion.

On the North Island of New Zealand, Fransen and Brownlie (1996) showed a particular example of the significance of *P. radiata* forests in catchment protection. In comparison with a catchment under pasture, the catchment under *P. radiata*

forests had much reduced area and intensity of soil slips. In another study, sixteen-year-old *P. radiata* managed for framing and biomass production afforded a level of protection superior to that of both intensively managed *P. radiata* and stands of regenerating native kānuka of equivalent age. In still later years and irrespective of differences in silvicultural practices, *P. radiata* would be expected to afford a high level of slope stability (Ekanayake et al. 1997). Many other studies have demonstrated the use of *P. radiata* as protection against the initiation of landslides and other forms of erosion (O'Loughlin 1984; O'Loughlin et al. 1986; Phillips et al. 1990; Marden et al. 1991; Marden et al. 1993). The effectiveness of *P. radiata* in catchment protection, slope stabilisation, flood mitigation and erosion control has been well recognised.

Introduction of *P. radiata* to the dry river valley area in Aba, Sichuan

Pinus radiata was introduced to the "dry river valley" area of Aba prefecture in 1990 as a part of the research work undertaken by Aba Forest Research Institute to search for the most suitable species for reforestation. Trees have been planted over a range of sites in the five counties: at elevation of 800-2600 m, slope of 10-30°, rainfall of 400-800 mm, evapotranspiration of 1000-1800 mm, mean annual temperature of 8-13.2 °C, maximum temperature of 32 °C, minimum temperature of -14 °C and soil with pH of 6.0-8.0.

These sites fall into four of the eight site classes defined by Aba Forest Research Institute for reforestation in the dry river valley area. In comparison to countries where *P. radiata* is successfully grown, the climate at these sites is largely within the range of climatic tolerance of *P. radiata*. However, the minimum temperature (-14 °C) at Aba is lower than that (-10 °C) in major production regions (Table 3), and slightly lower than -12.7°C, the minimum tem-

perature recorded for a clonal plantation at Korbel in northern California (Hood et al. 1980).

The first lot of seeds came from a seed orchard of New Zealand Forest Research Institute. Over the past 10 years, experimental plantations with a total area of about 128 hm² have been established in three counties of Aba prefecture. The overall survival rate three years after planting was about 90%. Five *P. radiata* nurseries have been established with a total capacity of producing 1.6 million seedlings per year in Wenchuan, Mao and Heisui counties. However, the provenances of these seedlings are unclear as the seed was purchased without information on genetic origin.

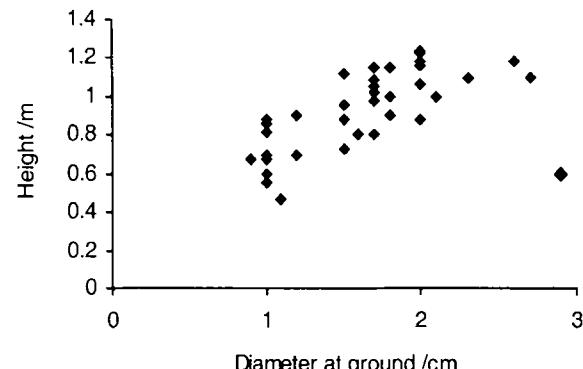


Fig. 1 Diameter and height of 2-year-old radiata pines planted at Xiao Gou, Aba

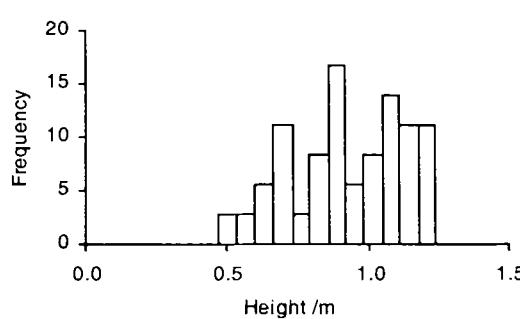
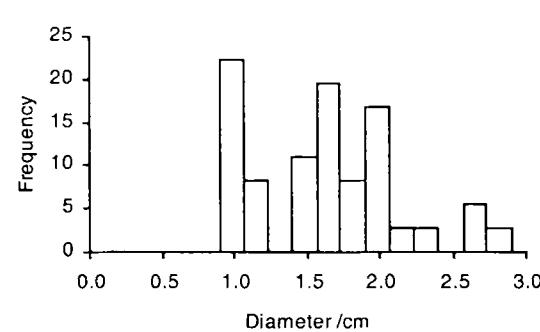


Fig. 2 Diameter and height distributions of 2-year old radiata pine stand planted at Xiao Gou, Aba

Pinus radiata generally performed much better than the native trees of both coniferous and broad leaf species. The native species screened by Aba Forest Research Institute included *Cupressus chengiana*, *Pinus tabulaeformis*, *Ailanthus altissima*, *Pistacia chinensis*, *Prunus armeniaca* and



Gleditsia sinensis. *P. tabulaeformis* was the best performing native species. However, *P. radiata* had much better survival and growth rates than *P. tabulaeformis* based on unpublished data of Aba Forest Research Institute (Fig. 4). The growing season for *P. radiata* also seems to be longer than

that for *P. tabulaeformis*.

The performance of *P. radiata* so far seems to be very promising in Aba. The average DBH (diameter at breast height) of trees in a 10-year old experimental stand was 16 cm. The DBH of the largest trees reached 32 cm, and the

tallest tree reached 16 m. Over the past 10 years, a substantial amount of research has been undertaken by Aba Forest Research Institute, which led to a workable system of nursery production, fertilisation, field planting and establishment silviculture.

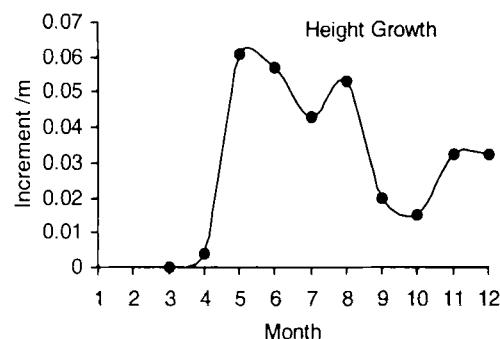
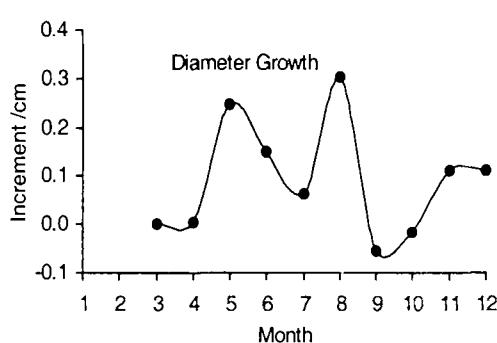


Fig. 3 Seasonal growth patterns of diameter and height of *P. radiata* stands at Xiao Miao San

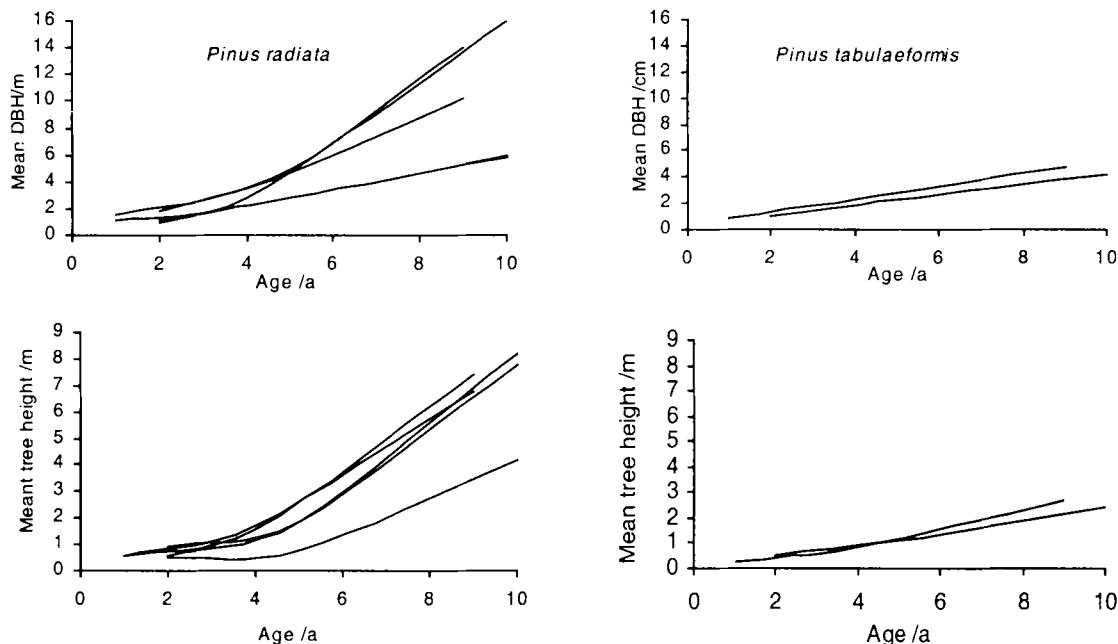


Fig. 4 Comparative growth rate of *P. radiata* and *P. tabulaeformis* in the dry river valley area of Aba prefecture, Sichuan, China
Curves represent stands at different locations

While much is known of the forest tree pathogens (e.g. Shao *et al.* 1997; Mao 1998) and forest insect pests (e.g. Xiao 1993) of China, there appears to be little published information on the pathogens and invertebrate pests of either *P. radiata* or *P. tabulaeformis* in the dry valley area. There has been limited evidence of forest health problems in the young *P. radiata* plantations. Trees in the field have been healthy in general. However, growing in the courtyard of the Forest Research Institute of Aba, there are two 10-year-old trees that have been infected by *Sphaeropsis sapinea* and *Pestalotiopsis* spp. causing some shoot die-back. The pathogens were isolated and identified by Mr. Xiao Yugui, forest pathologist at the Sichuan Forestry

Academy in Chengdu.

Conclusions

Although from a restricted natural range, *P. radiata* has proven to be adaptable to a much broader climatic niche. It has been successfully introduced as a plantation species to many parts of the world. At the same time, many unsuccessful introductions have highlighted the climatic, environmental and edaphic limitations and associated forest health risks posed to introducing *P. radiata* to areas beyond its ecological niche and beyond its range of biologically suitable growth environment. The climatic conditions of the

dry river valley area of Aba are largely within the range of climatic tolerance of *P. radiata*, which provides the basis for a successful introduction of *P. radiata* for afforestation to assist the recovery of forest ecosystems that have been destroyed.

The young *P. radiata* plantations in Aba, seemingly successful at present, can not be regarded as having passed through the preliminary phase of species introduction, particularly when cases elsewhere showed that early successes could be followed by later failures. Long term research and on-going monitoring are needed to help ensure a successful introduction of this exotic species to the dry river valley area for large scale afforestation. Two particular areas of concern that need to be addressed at present are forest health risk assessments and provenance testing.

At present there is little knowledge of the pathogens and invertebrate pests of either *P. radiata* or *P. tabulaeformis* in the dry valley area. For an introduced species, there will be a gradual loading of native pests and diseases as a result of the interactions between the exotic trees and native biological environment. An inventory of the pathogens and invertebrate pests of *P. radiata* in Aba prefecture would be extremely useful for the evaluation of potential loading of pest and disease to the introduced species over time. The inventory should concentrate on fungi and insect groups that are known to pose forest health risks to *P. radiata* elsewhere. When more information is available on the more significant pathogens and pests of *P. radiata* in Aba prefecture it will be feasible to screen families and clones for resistance and to better utilize site and genotype interactions for optimal survival and growth.

Many pests and diseases that cause significant damage to *P. radiata* plantations outside of its native range have not yet appeared in China. They include pests and diseases of *P. radiata* in its native environment such as the California pine aphid, *Essigella californica* Essig and pine pitch canker caused by *Fusarium circinatum* in California. It is important that every effort is made to prevent the introduction of these exotic pests and diseases to China. Contingency plans and control measures already developed in Australia for using against exotic pests and diseases as reviewed by Eldridge and Simpson (1987) will serve as a good reference for developing measures for pest and disease prevention for *P. radiata* in China.

The *P. radiata* currently being planted in Aba are from unknown and possibly inferior genetic stock. In order to ensure maximum success from this planting investment for the harsh sites, it is essential to have the best available germplasm. Climate modelling that integrates site, climatic information and knowledge on provenance performances through spatial interpolation will help define the working limits of *P. radiata*, particularly the limitations related to high altitude and long period of seasonal drought, in the dry valley area in the short term. Provenance testing in field trials will indicate the best sources of genetic material for growth and resistance to pests and diseases in the long run.

Climate modelling together with provenance testing will provide the basis for further selection and breeding to develop genotypic races for the environments in the ecologically degraded area.

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